Met Office
Hadley Centre

Advance

Improved science for mitigation policy advice

The new Met Office model increases our confidence that reducing greenhouse gas emissions quickly and to 50% of current levels by 2050 would make it possible to meet a 2 °C global warming limit.

Improving our understanding of how climate works

To provide credible scientific advice that underpins policy, we need to analyse all major parts of the Earth system, including the atmosphere, biosphere and oceans. Changes in climate depend on complex interactions between a range of Earth system elements. At the moment, computer models of the Earth system are the best tools we have for investigating and quantifying these relationships.

Having undergone a series of upgrades, the Met Office Hadley Centre's state of the art computer model — HadGEM2-ES — now includes parts of the Earth system that were not represented in our previous climate models. And it is only now that the importance of these components is being fully tested. The new model is allowing us to consolidate our understanding of how climate works and improve the quality of our climate projections.

This brochure reports on the first projections of future climate using the new model. These show that:

A peak in greenhouse gas emissions in the first decades of the 21st century, followed by 50% cuts in emissions by 2050, are compatible with a 2 °C global warming limit.

This backs up results from simpler models and considerably increases our confidence in this key conclusion.

The new model is being used to provide a more comprehensive analysis, building on previous work, to address science questions that affect policy. Our new model includes many important Earth system processes, but some are still to be added. So, while the science of climate projection is advancing, it is still far from complete. This brochure highlights just how important Earth system processes can be. We illustrate this with two examples, black carbon and ozone. Both have important regional impacts and a significant impact on global temperatures that are relevant to policy development.

This report ends with a look at some of the key questions that still need to be answered to underpin further policy development. We map out the next steps we need to take in computer modelling so that we can address these questions and provide more robust input to future IPCC[1] assessments.

[1] Intergovernmental Panel on Climate Change

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DEPARTMENT OF ENERGY & CLIMATE CHANGE

defra
Department for Environment Food and Rural Affairs

State of the art Earth system modelling is improving the quality of Met Office climate projections for policymakers worldwide.

Improved projections of 21st century climate

Earth system models are climate models that include key elements of the biosphere (biology of the land surface and ocean), and atmospheric and ocean chemistry. Many of these Earth system components are themselves affected by climate change and air pollution. These so-called 'Earth system feedbacks' can significantly alter the degree of warming caused by human emissions of greenhouse gases — or, alternatively, the extent to which we need to reduce greenhouse gas emissions in order to achieve a particular temperature target.

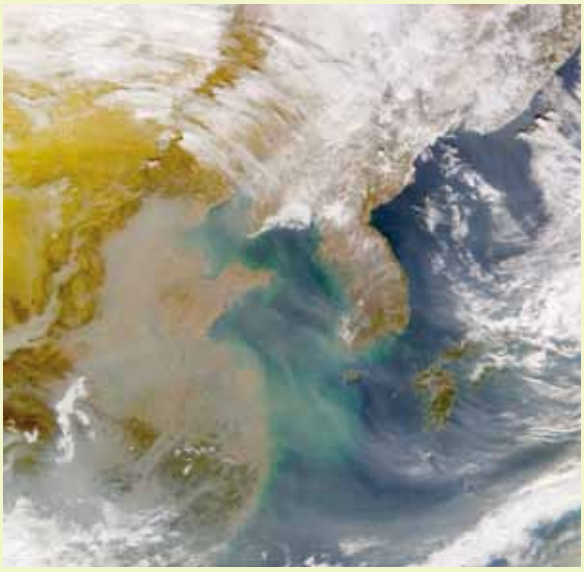
For example, warmer temperatures and changes in precipitation can reduce the uptake of carbon by plants and oceans, as well as accelerate soil decomposition. The resulting increase in carbon in the atmosphere leads to further warming. This is known as climate-carbon cycle feedback. The latest research shows that the combined impact of this and other Earth system feedbacks may be as significant as the long-recognised impacts of clouds and water vapour.

HadGEM2-ES is the latest Earth system model to be used at the Met Office Hadley Centre and is one of the world's most complex and sophisticated. It simulates many more potentially important Earth system processes than earlier models — many of which are still often used to provide advice on the effectiveness and side effects of mitigation policy.

WHICH PROCESSES DOES THE NEW MET OFFICE MODEL INCLUDE?

The table opposite shows some of the key Earth system processes that are included in the new model.

Right: A thick shroud of haze lingers over China, turning the sky an opaque grey and obscuring details of the land surface. Image courtesy of the SeaWiFS Project, NASA/Goddard Space Flight Center, and ORBIMAGE (see http://visibleearth.nasa.gov/view_rec.php?id=2477)



Earth system processes included in the new Met Office Hadley Centre Earth system model — HadGEM2-ES

CARBON CYCLE To date, natural land and ocean processes have absorbed about half of man-made CO_2. These processes are very sensitive to both changes in climate and atmospheric CO_2 concentrations, so Earth system models must include a fully coupled carbon cycle.	• **Land carbon uptake** Plant CO_2 absorption is enhanced at higher CO_2 concentrations and is also affected by climate change, depending on region. While high latitude warming may promote growth and lead to the expansion of boreal forests, hotter, drier conditions in the Tropics may lead to loss of rainforest. Decomposing organic material emits CO_2 — a process accelerated in warmer conditions.
	• **Ocean carbon uptake** CO_2 dissolves in seawater. While more CO_2 dissolves at higher concentrations, less CO_2 dissolves at higher temperatures. These two effects tend to offset each other. In addition, the amount of CO_2 in the surface waters is controlled by ocean circulation, which moves CO_2 into the deep ocean. Surface warming can lead to a weaker circulation, slowing CO_2 removal from the surface and, as a result, how quickly the CO_2 can be removed from the atmosphere. Biological processes, such as the presence of plankton, can also affect carbon distribution in the ocean and its uptake.
OTHER GREENHOUSE GASES	• **Methane (CH_4) emissions** from wetlands accelerate rapidly in warmer conditions, but may be reduced if conditions become drier.
	• **The lifetime of CH_4** in the atmosphere depends on how quickly it is oxidised. Its loss is more rapid in a warmer, moister atmosphere.
	• **Ozone** is an important greenhouse gas affected by chemical reactions involving other pollutants. It also damages plants (an effect not yet included fully in the model).
AEROSOLS These affect climate by scattering or absorbing the Sun's radiation and by affecting cloud formation. Some are produced by human activity; others are emitted by natural processes sensitive to climate change.	• **Windblown atmospheric dust** is an aerosol strongly affected by changes in soil moisture, wind and vegetation cover. It also nourishes some ocean plankton species, affecting the ocean carbon cycle.
	• **Some ocean plankton species emit dimethyl sulphide (DMS)** which can form sulphate aerosols, contributing to a cooling climate. This process is sensitive to changes in ocean conditions.
	• **Soot from combustion or 'black carbon'** absorbs sunlight, warming the climate. The deposition of black carbon on snow changes the reflectivity of the surface, which then causes more warming at high latitudes (an effect not yet included in the model).

The new model is advancing our understanding of climate change. The carbon cycle feedback is weaker, while some other climate feedbacks appear to be stronger.

The findings

Our new Earth system model can be used to project future climate change for a given pathway of future greenhouse gas concentrations, aerosol emissions and land-use changes. We're also using it to estimate what level of human CO_2 emissions could be permitted that are consistent with this pathway.

A new type of pathway is being used for the next IPCC assessment — the Representative Concentration Pathway, or RCP. This defines credible pathways of atmospheric concentrations of CO_2 and other greenhouse gases (taking account of the impact of aerosols) through time up to 2100. Results for two particular pathways are shown here, RCP 2.6 and RCP 8.5, representing very different views of how the world may develop (see box).

For the strong mitigation case, RCP 2.6, the Met Office model projects a peak global temperature rise of about 2.1 °C by 2050 (see diagram opposite). The global temperature then decreases slowly during the second half of the 21st century, as concentrations of greenhouse gases fall, but stays more than 1.5 °C above pre-industrial levels.

The Earth system model also allows us to link emissions to resulting temperatures, even though the pathway is specified in terms of concentrations. Our simulation confirms the findings from simpler models, that reducing CO_2 emissions by about 50% by 2050, compared to 1990, is consistent with limiting the temperature rise to around 2 °C. It also shows that it is important to reduce emissions further still, beyond 2050 and even 2100.

When interpreting these simulations we found that the climate-carbon cycle feedback in the new model is not as strong as it is in earlier, less sophisticated Met Office models. This means that higher emissions are consistent with a given CO_2 concentration pathway. This brings the new model more in line with estimates from other modelling centres featured in the last IPCC report. However, the new model is more advanced and more comprehensive than these earlier models, and we will need to reassess the likely range of this feedback once results from new versions of the other models are available.

RCP 2.6 (also known as RCP3-PD, PD = Peak and Decline) represents very strong mitigation

This comprises radiative forcing reaching a peak of 3.1 Wm^{-2} (approx. 500 ppm CO_2 equivalent) by mid-century, reducing to 2.6 Wm^{-2} (approx. 475 ppm CO_2 equivalent) by 2100.

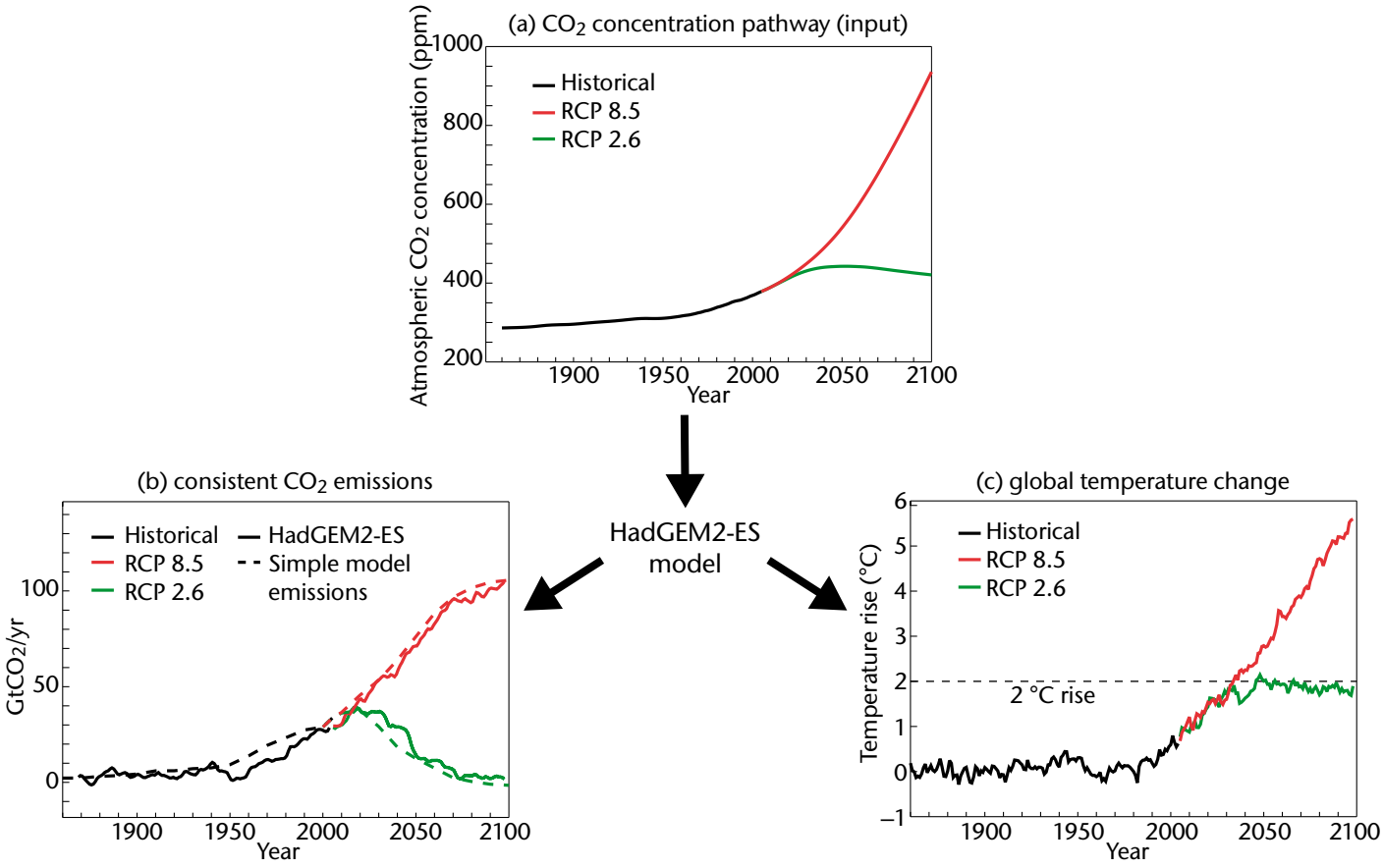
We would need a large and rapid shift away from the traditional use of fossil fuels to achieve the emission reductions for this scenario. This could involve a combination of nuclear power generation, renewable power sources, including biofuels, and the use of carbon capture and storage for many of the remaining fossil fuel sources.

RCP 8.5 represents 'business as usual'

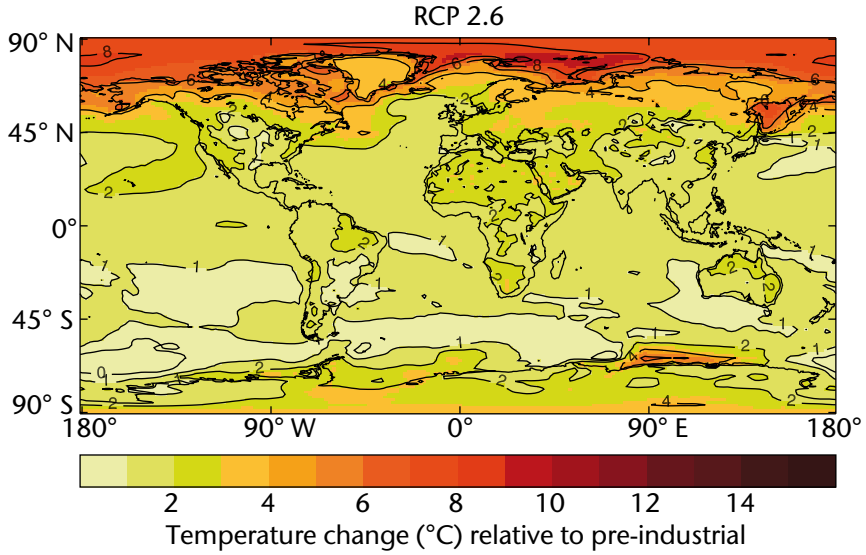
This scenario increases greenhouse gas emissions to bring about radiative forcing of 8.5 Wm^{-2} (approx. 1300 ppm CO_2 equivalent) by 2100.

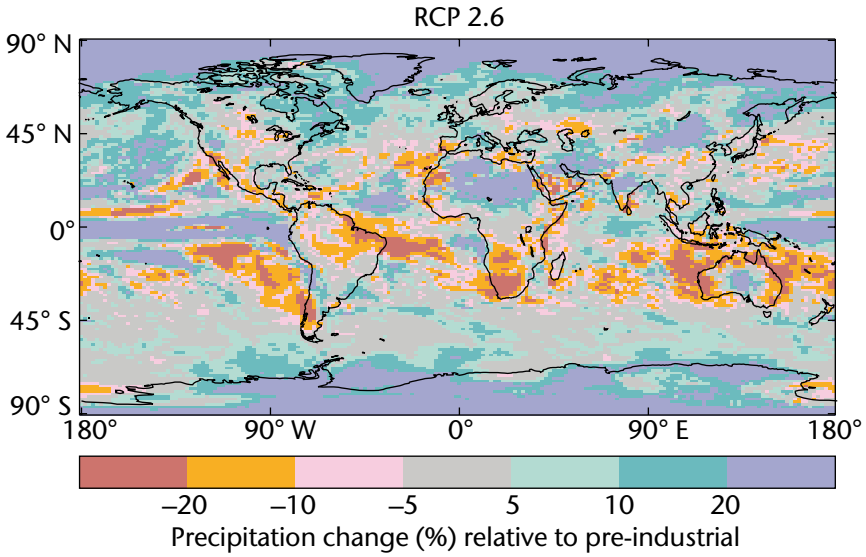
RCP 8.5 assumes that we continue to use fossil fuels with no mitigation.

Other climate feedbacks seem to be stronger, however. In idealised projections warming in the new model is about 30% higher than in earlier non-Earth system Met Office models, at a doubling of CO_2. Contributory factors could be differences in cloud feedback, uptake of heat by the ocean and changes in vegetation cover and land surface.



(a) Atmospheric CO_2 concentration pathways prescribed by the RCP 2.6 and RCP 8.5 scenarios. (b) CO_2 emissions that are consistent with each scenario as simulated by the Met Office model (solid line) compared to the simple climate models used to create the RCPs (dotted). (c) Global mean temperature change for each scenario in the Met Office model, relative to the pre-industrial (mean of 1860–1899).





Temperature rise and precipitation change at the end of the century (relative to pre-industrial average) for the Met Office model and mitigation scenario RCP 2.6.

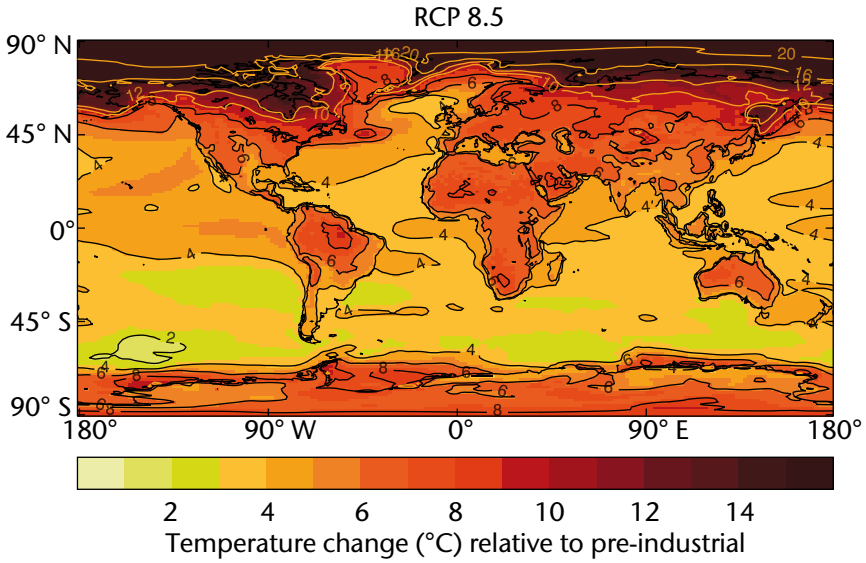
SPATIAL DETAIL IN CLIMATE RESPONSE

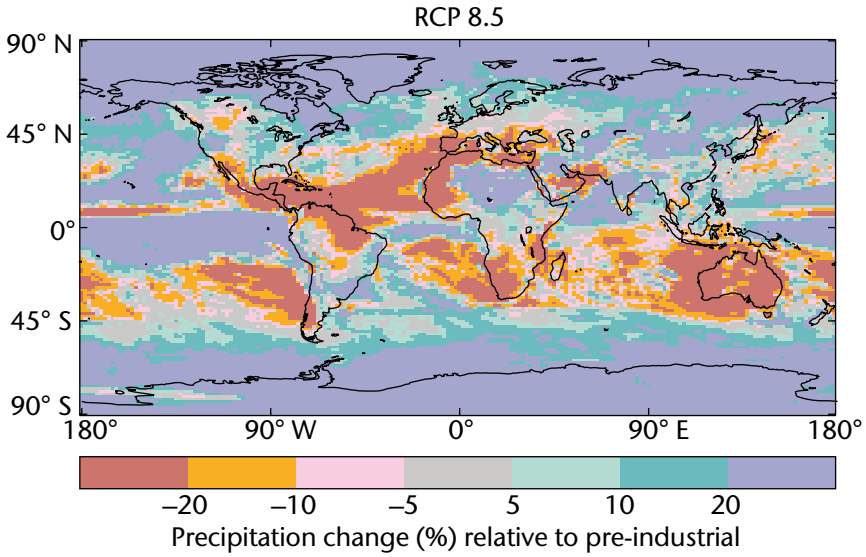
It is important to remember that while global average surface-temperature change is often used to indicate climate change, it is the spatial pattern of warming and associated rainfall changes that are more important because this is what impacts on ecosystems and society.

Although the global mean temperature rise for the strong mitigation scenario is between 1.5 and 2 °C by the end of the century, many regions will experience much greater (or lower) increases in temperature. For instance, Arctic increases of about 8 °C are possible in 2100 for this scenario. The average warming for land regions is 2.3 °C, compared to 1.8 °C for the global average.

If emissions continue to rise, leading to the RCP 8.5 scenario, then the global temperature is projected to reach 5.6 °C above the pre-industrial level by 2100 and is still rising by 0.45 °C per decade at the end of the century. Some regions are projected to warm by more than 15 °C (Arctic). The impacts of such a scenario are likely to be large and costly.

Rainfall changes will vary across the globe. For RCP 8.5, compared to RCP 2.6, these changes will be larger leading to much greater impacts, for example, on ecosystems, farming and human populations. The changes seen in these new simulations are broadly consistent with those reported by a number of models in the last IPCC report. Some regions, such as the Mediterranean and Australia, could experience less rainfall and greater frequency of drought, while others, such as northern Eurasia and Canada, could experience more rain or snowfall.





Temperature rise and precipitation change at the end of the century (relative to pre-industrial average) for the Met Office model and the business as usual scenario RCP 8.5.

SUMMARY

Simulations from the new Met Office Earth system model back-up previous estimates from simpler models. An emissions pathway that peaks early in the 21st century and reduces by about 50% by 2050 is projected to give a global average warming of around 2 °C during the 21st century.

As the new Met Office model represents more processes and gives a more realistic picture, we are even more confident that reducing emissions by this amount will avoid potentially dangerous climate warming levels.

Even so, it's important to bear in mind that these results come from just one model. Some additional processes still need to be included, and the results need to be compared with similar models as they are developed around the world. This will be a central element of the next IPCC assessment, to be published in 2013.

The warming effects from black carbon are amplified over high latitudes, where it darkens snow surfaces.

The importance of Earth system components

Case study 1: black carbon aerosol

WHY IS BLACK CARBON IMPORTANT?

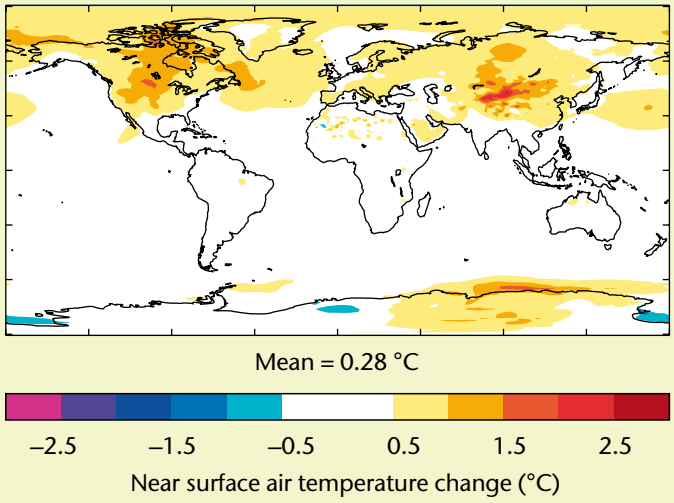
Black carbon (BC) has a potent warming effect in the atmosphere and may have significant regional consequences. Because it has a short lifetime in the atmosphere, reducing its emissions has the potential to reduce the rate of climate change in the short-term. For this reason, directly reducing BC as a way of mitigating climate change is now receiving policy attention at high levels. For instance, the G8 is committed to 'taking rapid action to address other significant climate forcing agents, such as black carbon.' *G8 declaration, 9 July 2009*.

WHAT IS BLACK CARBON?

BC is a type of atmospheric aerosol[2]. Many different natural and man-made combustion sources emit BC aerosol directly to the atmosphere. The largest include the burning of forests and savannas, solid fuels burned for cooking and heating, and diesel engines. Although industrial activities are also significant sources, aircraft and shipping only contribute to total emissions in a minor way.

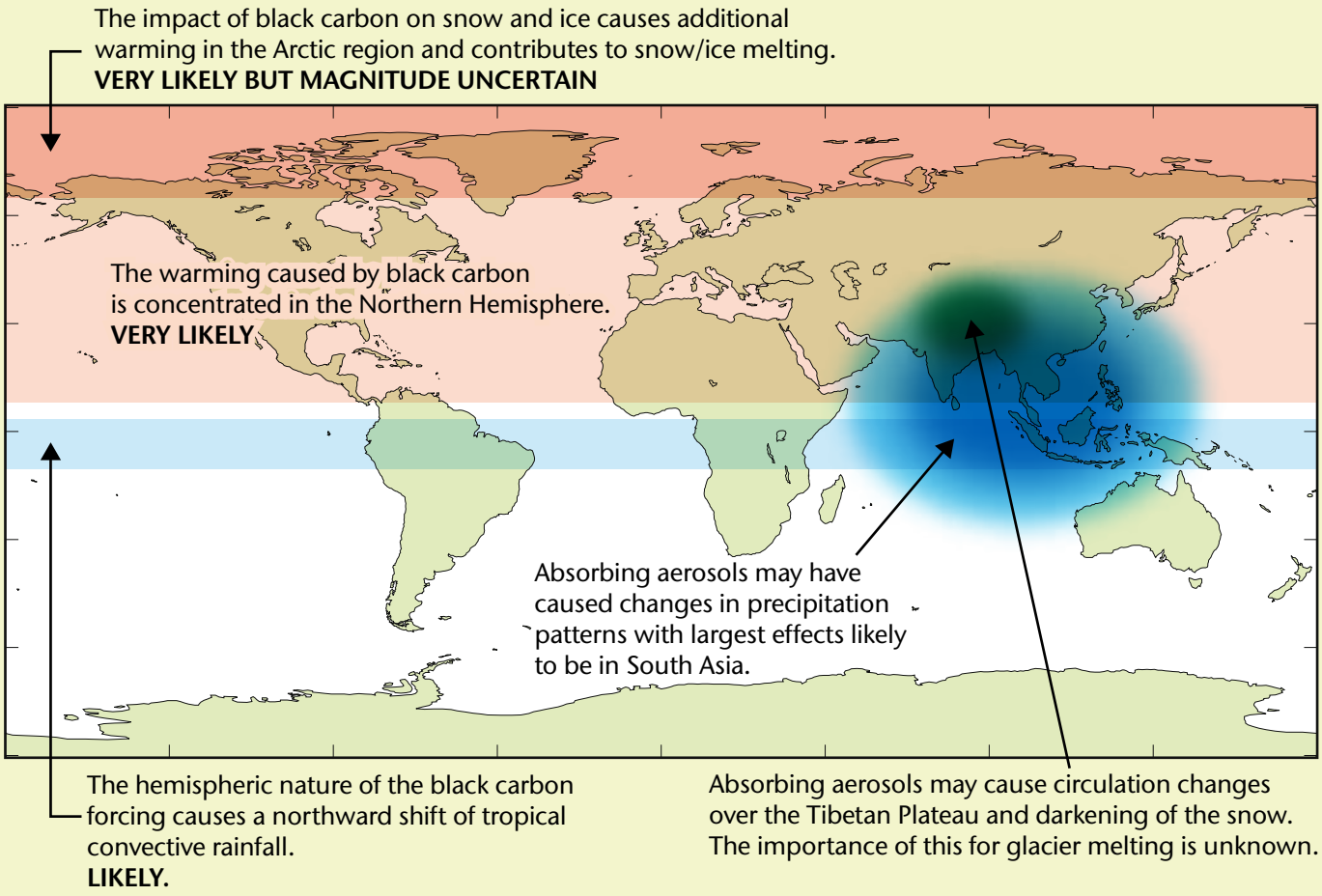
WHAT ARE THE EFFECTS OF BLACK CARBON?

BC aerosols are very efficient at absorbing sunlight, which heats the atmosphere. BC can also change cloud properties and cloud cover; and, if deposited in very cold regions, can darken ice and snow surfaces increasing absorption of sunlight. The net effect of BC on the climate is thought to be a warming. However, the magnitude of its effect and the exact role of BC on clouds are still unclear.



Equilibrium surface temperature change (°C) in response to the BC direct radiative forcing

[2] Small particles that exist in the atmosphere, from natural and man-made sources and varying in chemical composition (e.g. dust, sea-salt, smoke, sulphate).



Qualitative summary of our current understanding of BC aerosol climate impacts

HOW BIG ARE THE EFFECTS OF BC ON THE CLIMATE?

- **Surface warming**

The absorption of sunlight by BC causes a surface warming that is concentrated in the Northern Hemisphere. The Met Office Hadley Centre model estimates a radiative forcing of about 0.4 Wm^{-2} for the direct effect of fossil fuel BC and an equilibrium surface warming of 0.3 °C. The scientific consensus is for a range of 0.1–0.8 °C.

- **Snow albedo**

BC deposited on snow darkens the surface so that it absorbs more sunlight — the 'snow albedo effect'. Snow processes amplify this warming effect. The best estimate for global radiative forcing by BC in snow is 0.04 W/m^2 (range: 0.01–0.09 W/m^2). However, the 'snow albedo effect' is very efficient at warming the Earth's surface, compared with CO_2 forcing, so the associated warming is relatively large — 0.05–0.20 °C or possibly greater still. The impact is greatest during local spring and over mid to high northern latitudes. Warming from BC causes the snow to melt earlier in the spring, so the ground then absorbs more heat, which in turn leads to more warming at high northern latitudes.

- **Regional circulation and precipitation changes**

Different studies suggest that BC climate forcing causes regional circulation and precipitation changes. These include a northward shift in the Intertropical Convergence Zone and changes in Asian monsoon systems, where concentrations of absorbing aerosols are large.

Uncertainties in BC climate forcing and a lack of consistency in published climate model experiments mean we do not have a consistent view of the regional climate response to BC, either in terms of magnitude or the pattern of changes.

THE ROLE OF BLACK CARBON

Science can inform the policy discussion around the role of BC in the mix of greenhouse and other radiatively active gases. Analysis of species emitted with BC that have a cooling effect — sulphate and organic aerosols, in particular — also need to be taken into account. If emissions of co-emitted species are cut at the same time as BC emissions, the net effect will be less. Where mitigation of BC implies an increase in CO_2 emissions (i.e. a fuel penalty) we'll need to use appropriate indicators of climate change for a careful evaluation of the trade-off.

We need to include all the important Earth system feedbacks to be sure of the impacts of ozone and NO_X on climate and air quality.

The importance of Earth system components

Case study 2: importance of ozone

WHY IS OZONE IMPORTANT?

Ozone in the lower levels of the atmosphere has an impact on both climate change and air quality — something that is now being recognised by policymakers[3]. It is affected by, and affects many other, species important for climate change so is an ideal candidate for study with an Earth system model. Ozone has another very important role higher up in the atmosphere (not discussed here), where it absorbs energy from the Sun producing a warm, stable stratosphere and protecting the surface from harmful ultraviolet radiation. Changes in upper-level ozone — in particular, the 'ozone hole' — have been linked to man-made pollutants and the Montreal Protocol, agreed in the late 1980s, was put in place to protect upper-level ozone.

WHAT IS OZONE?

Ozone is a greenhouse gas. Its increase since pre-industrial times has contributed a present day forcing of 0.35W/m^2 compared to 1.66W/m^2 from CO_2. It is also an important air pollutant that affects air quality and at high concentrations is poisonous to people, animals and plant life. Ground-level ozone is formed in the lower atmosphere through the chemical reactions of pollutants, involving hydrocarbons and oxides of nitrogen (NO_x). Fossil fuel burning is a significant source of these pollutants as well as CO_2 which explains why human activity at least doubled the concentrations of ground-level ozone over the 20th century.

WHAT ARE THE EFFECTS OF OZONE IN THE CLIMATE SYSTEM?

Ozone doesn't just directly heat the atmosphere, it also plays a central role in the chemistry of the atmosphere. This means that the fate of ozone is tied directly to that of other greenhouse gas species, e.g. methane, all of which are linked through chemical reactions in the atmosphere.

[3] Air Pollution: Action in a Changing Climate, http://www.defra.gov.uk/environment/quality/air/airquality/strategy/documents/air-pollution.pdf

HOW BIG ARE THE EFFECTS OF OZONE ON THE CLIMATE?

Ground-level ozone damages plants, so has major implications for the ability of plants to take up CO_2. Lower plant productivity in polluted air means less carbon is stored in the plants and soil, so more CO_2 remains in the atmosphere. The climate change caused by this extra CO_2 can be as important as the greenhouse impact of the ozone itself. This means that air quality controls that limit ground-level ozone have a double benefit: on health and on climate.

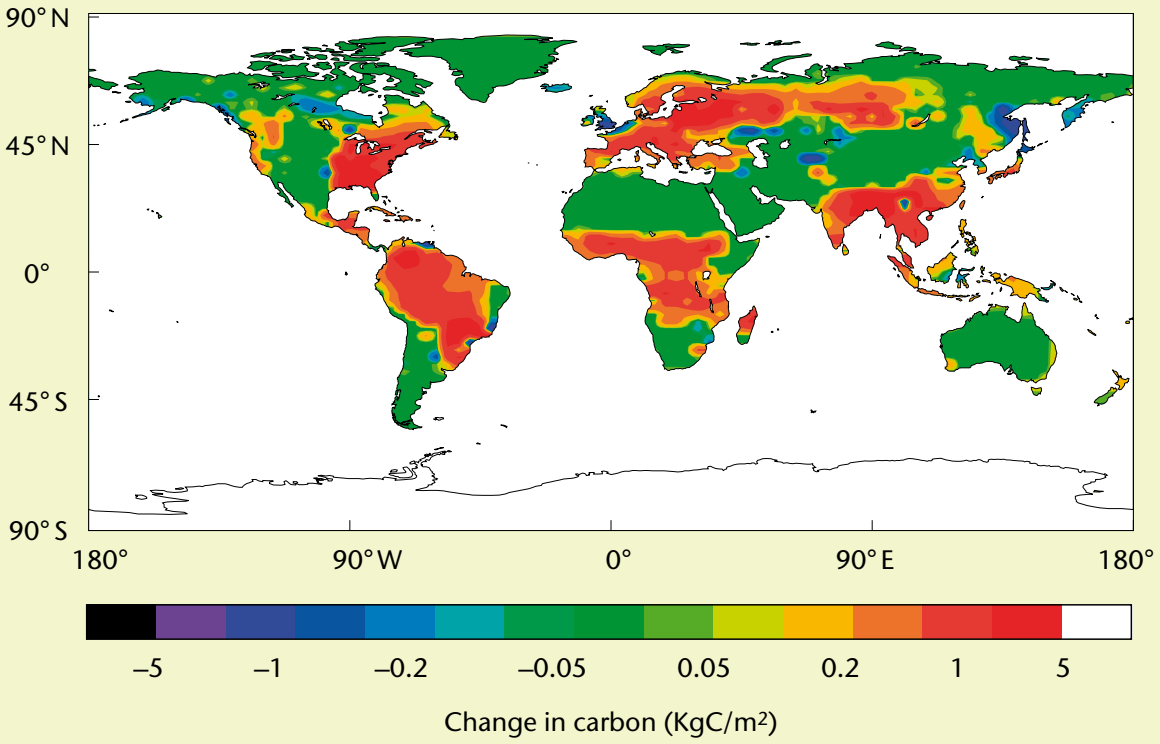
While extensive research has looked at the impact of ozone on plants in terms of crop yields, the Met Office Hadley Centre was the first to study its consequent impacts on global climate.

The figure below shows the increase in carbon stored on land (in vegetation and soils) if ozone pollution levels decrease as a result of planned air quality controls. These measures will slow down plant damage and therefore benefit climate. The improvements are largest over Europe and America where air quality legislation is most strict, and also over areas of large forests.

Unravelling the impacts of pollutants on climate is by no means straightforward. The most effective way to control ozone amounts would be to control emissions of nitrogen oxides (NO_X). But NO_X also destroys methane — a potent greenhouse gas, which, kilogram for kilogram, is 25 times more potent as a greenhouse gas than CO_2. Previous reports found that this effect dominates and, on balance, NO_X emissions cool climate[4]. However, these reports did not take into account the ozone damage to plants and its effect on CO_2.

When we include ozone damage to plants, the overall effect of reducing NO_X is to reduce global warming.

[4] IPCC 4th Assessment Report



The increase in carbon stored on land (in vegetation and soils) due to air quality controls by 2050. The difference in land carbon (kg(C)m^{-2}) in 2050 between the IIASA scenario, in which planned air quality controls in current legislation are adhered to (Royal Society 2008), and the SRES A2 scenario in which ozone pollution is uncontrolled.

Given their major implications for international technology and economic development, policy decisions on climate change must be underpinned by the best possible evidence.

Future Earth system science to underpin policy development

Thanks to the latest generation of Met Office models, we already understand more about how man-made emissions of greenhouse gases are linked to global and regional temperature during the 21st century. Our results and, therefore, our conclusions are more robust and this has strengthened our confidence in results from simpler models. The latest models also allow us to add more information about complex interactions involving different pollutants — information that is critical for answering specific policy questions. Results from the new model are now emerging and will be fed into the next IPCC Assessment Report to be published in 2013.

We have looked at two examples of important Earth system processes: those involving black carbon aerosols and ozone damage to plants. Controlling black carbon emissions may be a way for policymakers to regulate global warming over the short-term. Ground-level ozone is a greenhouse gas in its own right and affects CO_2 through its impact on plants. Its lifecycle is strongly coupled to other air pollution species, such as NO_X. Our results now suggest that there may be benefits in treating climate change and air quality policy together.

We will continue to improve the representation of processes included in our model. There are also a number of processes not currently included that could potentially have a major impact on the degree of warming for a given emissions scenario, quite apart from their impact on local and regional climate. Some of these processes have been discussed here and we are actively working on including them in the model:

- The impact of ozone on plants reduces their ability to take up carbon.
- The deposition of black carbon on snow changes the reflectivity of the surface leading to more warming at high latitudes.

Other processes are less well understood but are actively being researched with a view to including them in future models:

- The ability of plants to take up carbon may be limited by the supply of nitrogen available naturally, but may be enhanced by man-made sources of nitrogen. Climate change itself may also increase available nitrogen and stimulate plant growth.
- The thawing of permafrost may lead to large amounts of carbon release, but these processes are not well understood.
- Dynamic ice processes could speed up freshwater supply from glaciers into the ocean.
- The processes that affect methane in the Arctic Ocean could lead to increased methane release (the science is poorly understood so may take longer to include in models).

The international science community is working hard to understand and narrow the uncertainties in future climate projections — and it is doing this primarily through model intercomparison projects, comparison with observations, and the synthesis of results by the next IPCC report.

Understanding the interactions within the Earth system is critical.

Met Office working in partnership

Editors: Vicky Pope, Jason Lowe, Lizzie Kendon, Fiona Carroll, Sarah Tempest

Contributing authors: Olivier Boucher, Bill Collins, Chris Jones, Lizzie Kendon, Spencer Liddicoat, Jason Lowe

Met Office
FitzRoy Road, Exeter
Devon, EX1 3PB
United Kingdom

Tel: 0870 900 0100
Fax: 0870 900 5050
enquiries@metoffice.gov.uk
www.metoffice.gov.uk

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